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Department of Psychology
University of Illinois
Champaign, Illinois 61820

COGNITIVE PSYCHOPHYSIOLOGY LABORATORY

Technical Report No. CPL80-1/AFOSR8-1

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APPLICATIONS OF EVENT RELATED BRAIN POTENTIALS IN HUMAN ENGINEERING ANNUAL PROGRESS REPORT:

EMANUEL DONCHIN AND CHRISTOPHER WICKENS
COGNITIVE PSYCHOPHYSIOLOGY LABORATORY

Prepared for:
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This report describes research partially or entirely conducted during the first year of the contract period. It describes experiments related to four basic categories of human performance research: (1) attention (including both attention allocation and workload), (2) subjective probability and expectancy, (3) processing latency, and (4) control movement. A series of appendices describes those portions of the research that have been completed.

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Table of Contents

1. Introduction

The following report describes the research conducted by the Cognitive Psychophysiology Laboratory on Air Force Contract #F 49620-79-C-0233: Applications of Event-related Brain Potentials in Human Engineering, during fiscal year 1980. This research has proceeded from two perspectives (1) we have identified certain problem areas in aviation and man-machine system design (e.g. workload, display optimization), and have directed research paradigms to address these issues, (2) we have continued to explore more basic issues in understanding the vocabulary of the event-related potential, and the experimental variables that influence its various components. The specific investigations we have conducted however, can not be neatly classified into one category or the other, but instead span the continuoum that may be defined between those two endpoints. Thus, the investigations described below will be organized instead in terms of four basic categories relating to dimensions of human information processing: attention, expectancy and subjective probability, processing latency, and movement. Experiments within a category share that feature in common, even though they may be quite disparate in terms of their degree of immediate applicability to human engineering problems, or the specific nature of that appliction.

It should be noted that of the experiments described below, some are relatively complete, in terms of preparation of a final manuscript, while others are still in intermediate stages of completion. Those in the former category are only described in very brief detail here, and the reader is referred to the appendix in which the manuscript appears for details. Those in the latter category will be described in more detail here.

2. Review of Research Investigations

2.1 Attention.

The limits of human operator attention represent a major bottleneck in the performance of many complex man-machine systems. Because previous research has repeatedly demonstrated the sensitivity of components of the ERP to attentional manipulations, we have identified attention as an area with a high potential payoff for applicability of ERPs to human engineering questions. One area of applicability concerns the selective aspects of attention to information in a display, a second relates to its intensive aspects and concerns the measurement of workload.

2.1.1. Attention Allocation in Complex Displays. When an operator is engaged in a display monitoring task, our research has addressed the extent to which ERPs elicited by elements within that display, reflect the degree to which these are attended or ignored. (For an overview, see Appendix A).

2.1.1.1. Passive Assessment. (for details, see Horst & Donchin, Appendix B). The intent of this experiment was to determine whether it was possible to infer the direction of gaze, without requiring active processing of information within the display. Drawing upon the prior research of Jeffries, our investigation established that the presence of a visual stimulation (a flashed checkerboard) in the upper vs. lower half of the visual field could be reliably discriminated on the basis of the amplitude of early components of the visual ERP. Applying discriminant analysis, the data suggested furthermore, that single trial ERPs could be

discriminated with 80-90% accuracy in terms of the half field of stimulation. These results suggest that the locus of fixation of gaze, above or below the center of a display could be reliably assessed by repeatedly stimulating that center position, and inspecting the resultant ERPs.

2.1.1.2. Allocation of Attention to Relevant and Non-Relevant Events Within a Visual Display. This research continues a program investigating the difference in P300 amplitude between relevant and non-relevant "aircraft", in a simulated air traffic controller display. Previous research had indicated that P300 amplitudes were greatly influenced by attention allocation instructions in a display in which both relevant and non-relevant items were moving and continuously visible. The present experiments were directed toward a more refined understanding of the nature of this attention effect, and towards the identification of variables, such as event probability or frequency, which might attenuate or amplify the magnitude of this effect.

The particular visual monitoring task was selected as representative of a large class of tasks performed by operators of contemporary man-machine systems. The primary question addressed by this research is whether relationships between P300 and task variables in experiments utilizing simple displays would generalize to a broader range of parameters found in more complex systems.

General Method: Subjects viewed stimuli presented on a low-persistence cathode ray tube driven by a computer-controlled graphics system. In the Continuous display condition, two squares and eight

triangles were continuously viewable throughout each monitoring period. Each square and triangle moved across the screen at a different trajectory from left to right. When the element reached the border of the screen, it disappeared briefly and then reappeared at a new random location on the left border. The symbols traversed the screen several times during each monitoring period, which lasted three to four minutes.

Signals consisted of brief intensifications of one of the elements. Only one element flashed at a time. The flashes lasted 200 milliseconds and were easily perceptible. The interval between flashes and the relative probability that a square vs. a triangle would flash were varied between monitoring periods.

In all cases, the subject's task was to mentally count the number of flashes for the squares and to report this number at the end of each monitoring period. Subjects were instructed to ignore the triangles. The experimenter emphasized that the triangles were not task relevant and that the subject would never be asked anything about them. The stimuli and task were designed to elicit nearly perfect performance (count accuracy) from the subjects.

The Periodic display condition was identical to the Continous condition except the squares and triangles were viewable only when a flash occurred. At all other times, the screen was blank. Thus, the subject saw only a snap-shot of the two squares and eight triangles, with one element intensified, at the particular interstimulus interval. In the Periodic condition, the subject could not track relevant elements prior to a flash, as was possible in the Continuous display condition.

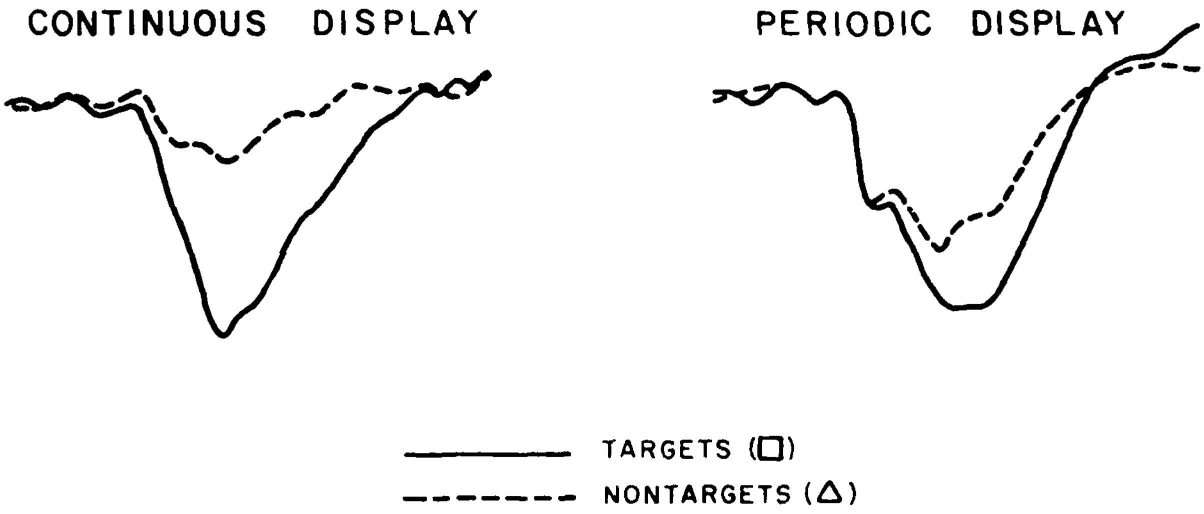
Experiment 1: Event Probability and Display Format. Heffley, Wickens and Donchin (1978) examined the effects of selective attention, event probability, and display complexity on P300 in Continuous display conditions. The target flashes elicited consistently large P300 components and the nontarget flashes elicited little or no P300. Thus, the amplitude of P300 was related to the subject's ability to selectively attend to the targets. The amplitude of P300 was not sensitive to the relative probability of target and nontarget flashes, however. This failure to observe a probability effect contrasts with reports of an inverse relationship between event probability and P300 amplitude that is independent of whether the signal is a target or nontarget in the "oddball" paradigm.

In Experiment 1, Periodic display conditions were included in order to determine whether the failure to observe a probability effect in the previous experiment was due to the subject's ability to essentially filter out nontarget events based on spatial position. In the Periodic condition, the subject was compelled to process each bright element, regardless of whether it was a target or nontarget.

The effects of selective attention, display format and event probability are apparent in Figure 1. The waveforms for the Continous display condition illustrate the dramatic effect of selective attention to target elements on the P300.

In the Periodic condition, both targets and nontargets elicit substantial P300 components. The increased response to nontargets in the Periodic condition is apparent in the graph of P300 amplitude. This increase presumably reflects the processing associated with these

SELECTIVE ATTENTION
and
EVENT PROBABILITY
(12 subjects)



DISPLAY CONDITION & EVENT PROBABILITY
($\overline{ISI}$= 6 seconds)

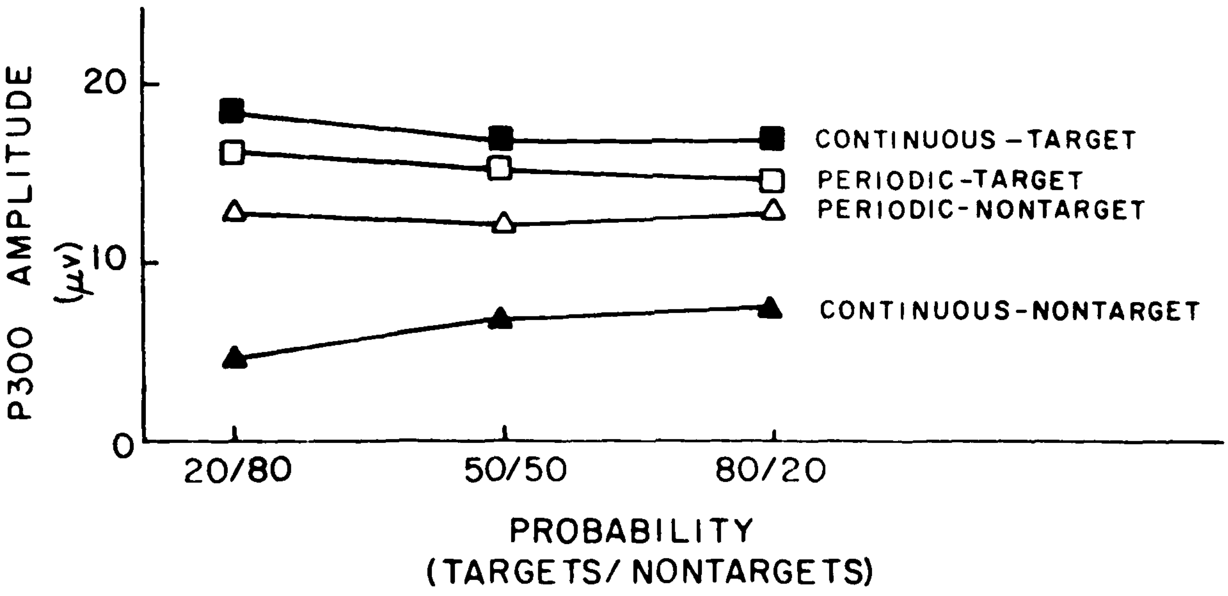


FIGURE 1

task-irrelevant signals which cannot be selectively ignored with the Periodic display format.

Although the subjects were compelled to process both targets and nontargets in the Periodic conditions, an inverse relationship between event probability and P300 amplitude did not emerge. The lines for targets and nontargets remain almost parallel across probability levels. Thus, the results of the probability manipulation in this experiment are at variance with previous reports of experiments utilizing the "oddball" paradigm with shorter interstimulus intervals.

Experiment 2: Event Probability and Interstimulus Interval. The second series of experiments examined the interaction between event probability and interstimulus interval. Although temporal uncertainty is thought to play little role in P300 generation (McCarthy & Donchin, 1976), interstimulus interval became an increasily likely explanation for the failure to observe a probability interaction. Therefore, subjects were tested in the Periodic display condition in four types of blocks: the ISI at 3.0 or 1.3 seconds, and the global event probability at 20/80 or 80/20.

The results indicate that interstimulus interval is indeed a significant determinant of the probability effect, as illustrated in Figure 2. At a 3.0 second ISI, there is a small probability interaction. At a 1.3 second ISI, there is a significant interaction which is similar to the effect commonly observed in P300 "oddball" paradigms. In addition, it is perhaps important to note that targets elicit slightly larger P300 components relative to nontargets at equivalent event probabilities.

EVENT PROBABILITY
and
INTERSTIMULUS INTERVAL
(periodic display - 9 subjects)

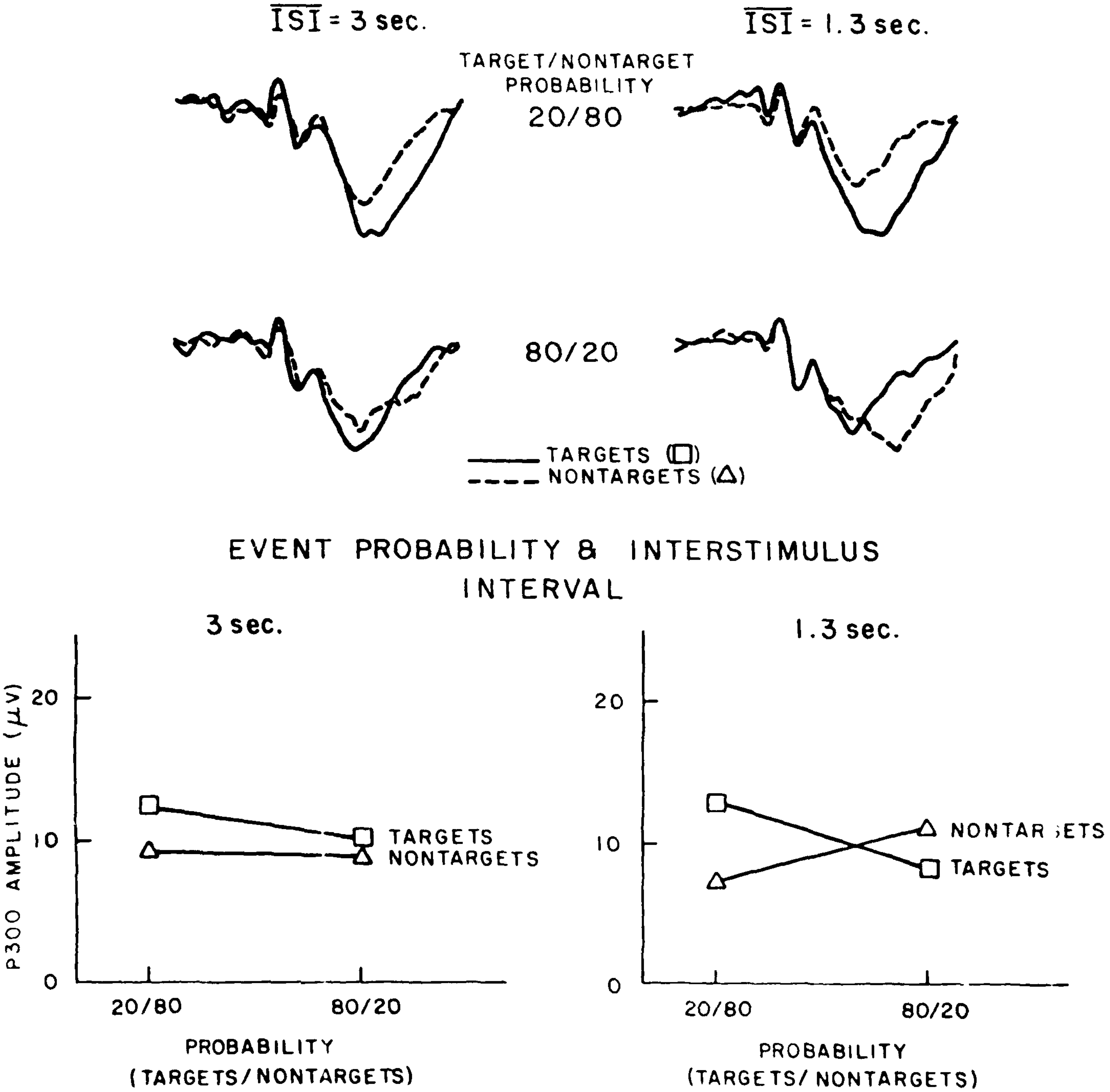


FIGURE 2

Discussion: The experiments presented in this report expand upon our knowledge of P300 from previous experiments utilizing simple, relatively static visual displays. Selective attention, event probability and interstimulus interval interact to produce significant effects on P300.

The differences in responses to nontargets in Continuous and Periodic display conditions illustrate the effect of selective attention on P300. The ability to filter out irrelevant signals results in greatly reduced P300 amplitude.

At long interstimulus intervals, the "target effect" predominates and there is little effect of probability on P300 amplitude. As the ISI is reduced, the "probability effect" emerges. When the ISI is approximately one second, the target effect is small and the probability is the most significant determinant of P300 amplitude.

The interaction between event probability and interstimulus interval suggests that P300 can be dependent upon a short-term memory process. The modality of stimulation becomes a significant factor within this context. Visual short-term memory duration is thought to be on the order of a very few seconds. The data in this report are consistent with this estimate. Auditory short-term memory is believed to last much longer. Squires, Petuchowski, Wickens and Donchin (1977) present evidence for an interaction between modality and stimulus sequence in the determination of P300 amplitude. The effect of modality and interstimulus interval are currently being more fully explored.

The results of these experiments indicate that ERPs, and P300 in particular, may find significant applications to problems in

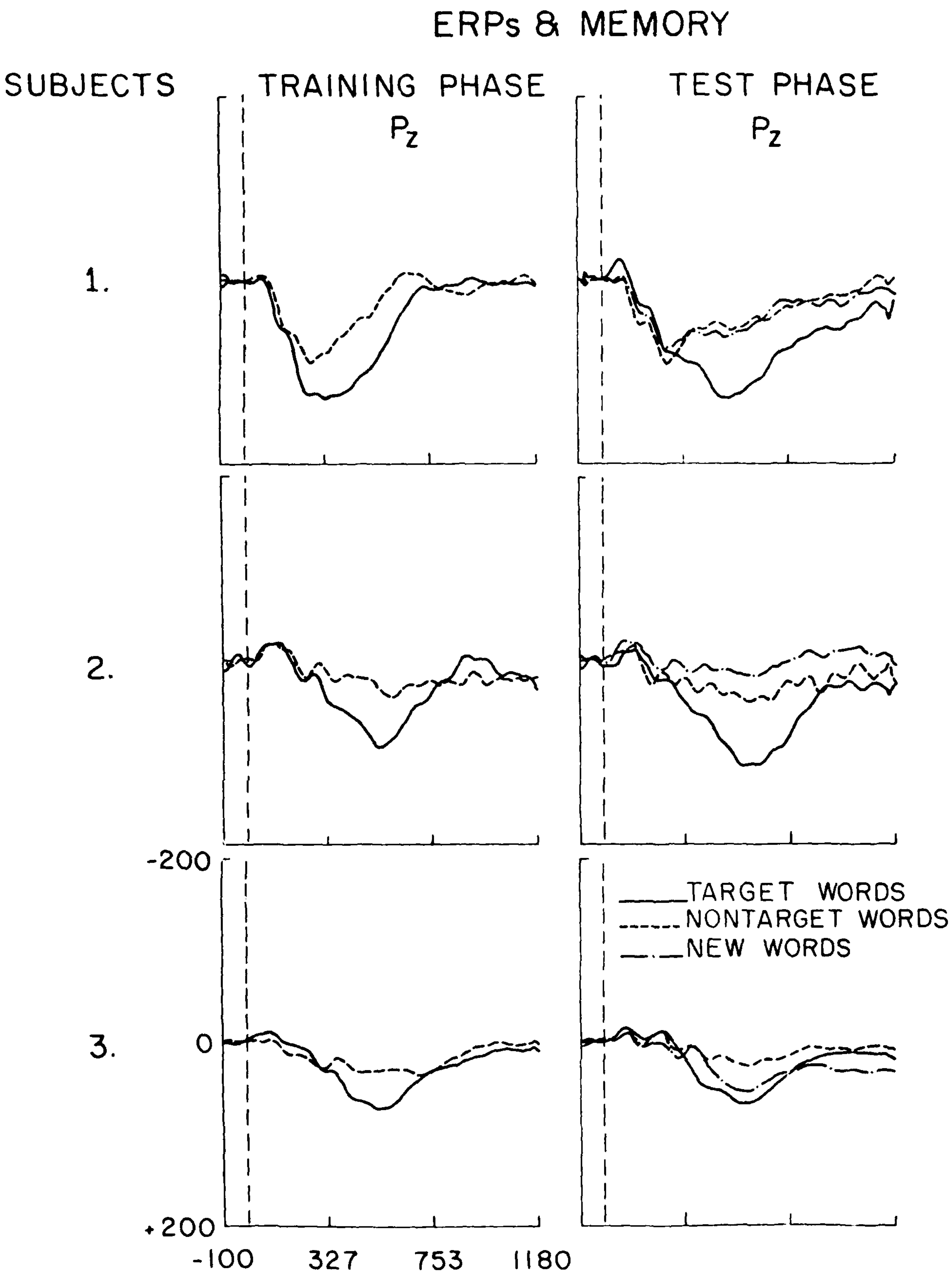
man-machine systems design. The ability to assess the efficiency of the operator's selective attention may be especially valuable in the design of high information-load systems. As understanding of the relationship between P300 and task variables expands, we move closer to this realization.

2.1.1.3. Attention Allocation in Learning. The studies described above have focused upon the differential allocation of attention to simultaneous elements in a display. Attention is equally important in learning and memory. If an operator is provided a series of items or events to commit to memory, we can assume that those items that are attended, will be better remembered than those that are not. We ask in the present series of experiments if the P300 can reflect the relations existing between learning, memory and attention. More specifically, our principle interest is in determining whether P300 amplitude is correlated with later recognition or recall. That is, can we predict, for individual items, in a memorized list, the probability of successful recognition or recall during a memory test based on the P300 amplitude elicited by these items during a previous learning trial.

Design: In our first experiment we used lists of words. There were two lists in each trial: a training list and a test list. Words were presented to the subject sequentially, with an ISI of 2 seconds, and EEG was recorded from Fz, Cz, Pz, and Oz. In the training list half the words were brightly illuminated and half were dim, although both were easily readable. The sequence of bright and dim words was randomly determined. Half the subjects were told to remember the dim words, half the bright words. Five seconds after the training list ended the test list began. It

was composed of all the words in the training list plus an equal number of new words. Once again, the order of words was randomly determined. In this phase subjects held a box with two buttons. Half the subjects were instructed to press the right button whenever one of the words they were instructed to remember appeared ("memory" words) and the left button for both "new" and "ignore" words. The new words had not been presented in the training list; ignore words had been previously presented, but these were the words the subject was not requested to remember. The other half of the subjects were instructed to press in the reverse order. Subjects were told that they should respond quickly, but that accuracy was more important than speed. After the test list there was a brief rest interval (10 or 15 seconds) and then the cycle repeated with the presentation of another training list. Words that appeared in the training or test list of one trial never appeared in any other trial. After several trials the subject was asked to recall as many of the memory words as he could. Subjects were told to expect this free recall, but that it was secondary to the main task of correctly categorizing each word in the test phase of each trial. Lists in the first experiment had 4, 8, or 12 words in the training list (and thus 8, 16, and 24 in the test list).

Results: Averages from Pz for the first 3 subjects are presented in Figure 3. In the training phase (on the left side of the figure) a larger P300 is elicited by the memory words. This is also the case in the test phase where, in addition, there appears to be little difference between the new and ignore words. Unfortunately, we cannot make the comparison of greatest interest, between ERPs to memory words in the training phase that were later correctly recognized or recalled and those



ERPs & MEMORY
SUBJECTS
TRAINING PHASE
TEST PHASE
Pz
Pz
1.
2.
3.
-200
0
+200
-100
327
753
1180
TARGET WORDS
NONTARGET WORDS
NEW WORDS

FIGURE 3

that were not. This is impossible because the task was too easy and subjects made very few errors, (almost all words were correctly categorized). We are now using longer lists, with up to 30 words in the training list. It will also be informative to compare the ERPs of memory words in the test phase that were recognized with those that were not. Even though a subject may categorize a memory word incorrectly, is the ERP like those elicited by other memory words, or is it more similar to one of the other categories? Reaction time may also provide information in such situations, especially when combined with the ERP data.

In the experiment reported, the subject was told to remember only the memory words, and in the test phase was not asked to discriminate between the ignore and new words; the same button was pressed for both classes. We are now adding a recognition test, which will only be given at the very end of the experiment, to determine if the subject can distinguish between these two classes. This will permit us to divide the ERPs to ignore words in the training phase into two categories, those correctly recognized and those not.

Control Conditions: We will have to run several control conditions. These will include having the subject just count (and not trying to remember) either bright or dim words, and having the subject remember everything in the training phase, not just half the words. We will also want to manipulate the proportion of memory words in both the training and test phases to ensure that the differences we find are not due to probability effects.

Additional Experiments: We will want to extend this work in several ways. We can use a variety of stimuli in addition to words: nonsense syllables, nonsense figures, pictures of common objects, line drawings, and so on. If we use both pictures and words it will also become interesting to examine hemispheric differences, and relate these to the behavioral findings on laterality differences between spatial and verbal material.

2.1.2. Attention and Task Workload. While the above experiments have been concerned with the selective aspects of attention, we have also pursued research on its intensive aspects: examining attention as a limited commodity resource in the measurement of task work load. P300 amplitude has been employed as a measurement of residual capacity, available in the performance of primary tasks.

2.1.2.1. Tracking Difficulty: Order of Dynamics. Isreal, Wickens, Chesney and Donchin (1980), demonstrated that the amplitude of P300 to auditory probe stimuli could serve as a reliable index of display processing load. Using a similar paradigm, Isreal, Chesney, Wickens and Donchin observed that P300 was not sensitive to increases in tracking difficulty induced by increasing the bandwidth of the random forcing function to be tracked. The joint conclusions drawn from these two investigations was that P300 could serve as a selective index of perceptual processing demands, but not those demands associated with response selection and execution.

A further study was therefore conducted to assess whether P300 amplitude would be sensitive to changes in the order of the

control dynamics of the tracking task. We inferred that, when tracking second order dynamics, subjects are required to generate lead, or process the higher derivatives of the error signal, in order to stabilize the system. Such an increase in the demands upon the perceptual processing system should, therefore, lead to an attenuation of P300 not observed with the bandwidth manipulation. In experiment 1, subjects tracked alternatively with 1st and 2nd order dynamics, while counting auditory probe stimuli. The ERPs to the counted stimuli, recorded at Pz and shown in figure 4, indicate indeed that the amplitude of P300 was attenuated from the control (count only) condition, to 1st order tracking of greater importance, P300 reliably ($p < .03$) declined from 1st to 2nd order tracking. This was in contrast to the absence of such an effect observed when bandwidth was manipulated in the previous investigation of Israel, Chesney, Wickens and Donchin (1980).

To make a strong test of the contrast between the two independent variables, five of the same six subjects who participated in experiment 1, tracked in experiment 2, in which bandwidth was manipulated while ERPs were again recorded. There were two versions of this experiment. Both employed only 1st order dynamics. In one version bandwidth was increased to a level that generated equivalent error for each subject, to the error obtained in 2nd order tracking from experiment 1. In essence this procedure was used to equate the magnitude of tracking difficulty manipulations between the two experiments. When this was done, figure [illegible] indicates no reliable difference between ERPs in low and high bandwidth tracking (in fact there is a slight reversal). This replicates the results of Isreal, et al. In the second version, bandwidth was increased to an even higher level in the high bandwidth condition, such that tracking error was

Figure 4.

AUDITORY ERP's RECORDED AT C_z

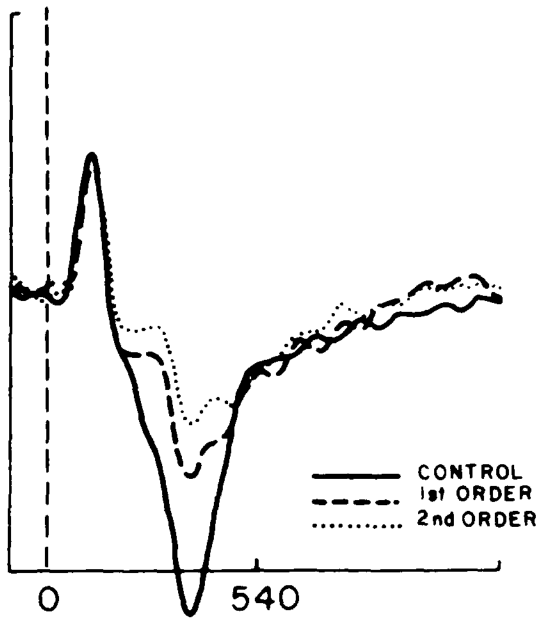


Figure 5.

AUDITORY ERP's RECORDED AT P_z

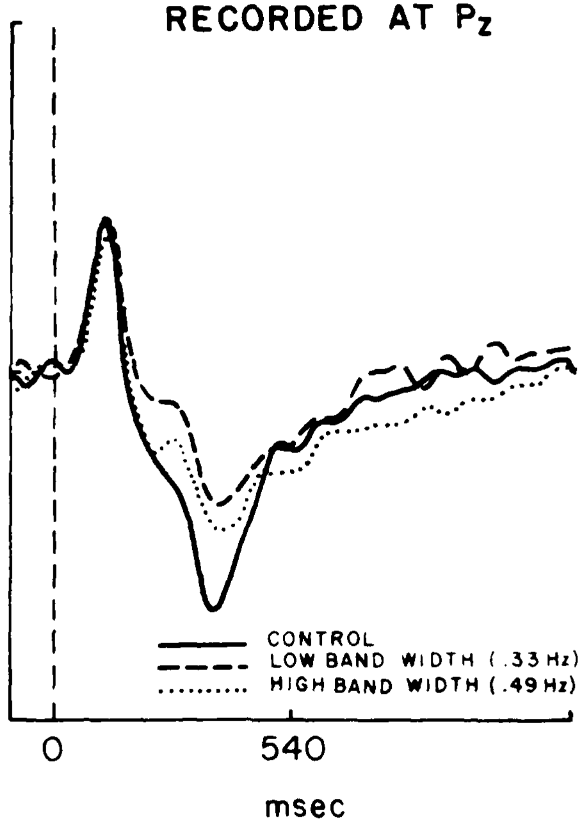
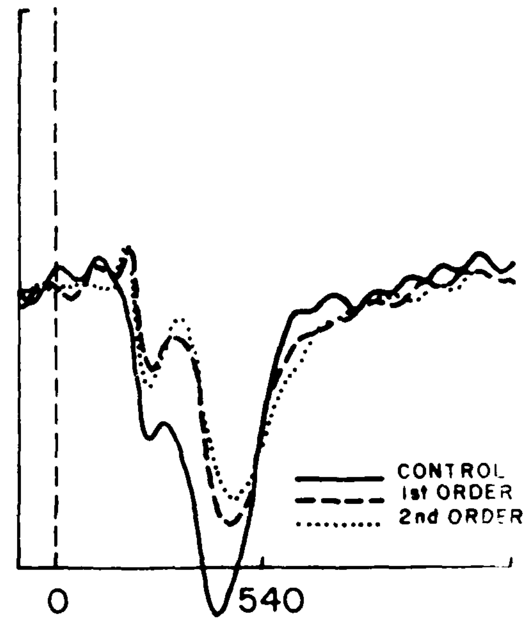


Figure 6.

VISUAL ERP's RECORDED AT C_z



greater than it had been in the high order condition of experiment 1. Under these conditions a small decrease in P300 was observed at the high bandwidth level.

The joint results of the three experiments suggest that tracking order imposes a reliable load upon perceptual resources. These resources also underlie processes reflected by P300 amplitude. Tracking bandwidth draws to a greater extent upon resources of a separate functional composition. However, at sufficiently high levels of bandwidth, perceptual resources are consumed as well.

2.1.2.2. Primary Task and Probe Modality: Control Order. An additional condition in experiment 1 of 2.1.2.1. replicated the manipulation of control order, but employed visual probe stimuli (bright and dim intensifications of the horizontal tracking axis) instead of auditory probes. This comparison was made to assess whether the sensitivity of the ERP to primary task processing demands was enhanced or attenuated when within-modality probes were employed. The results are reflected by the waveforms in figure 6, and may be contrasted with the auditory results in figure 4. These indicate that while the amplitude of the single task visual ERP is equivalent to that of the auditory, it is attenuated less by the introduction of the tracking task than was the auditory. Furthermore, unlike the auditory probe results, the visual ERP appears to be unaffected by the order of the tracking dynamics. Workload effects, as observed here appear then to be more accurately reflected when cross- rather than within-modality probe stimuli are employed.

Primary Task and Probe Modality: Auditory Tracking. The cross-intra modality effect described above was explored in greater detail in a second series of experiments. These are described in detail in Appendix C, (Isreal, 1980).

In Isreal's experiment 1, the interference within and between sensory modalities was examined with a tracking and reactions time task. Subjects performed either an auditory or visually displayed tracking task, concurrently with a go/no-go reaction time task to auditory or visual stimuli. These stimuli in turn required either spatial or intensity discriminations. The results indicated that there was greater competition for resources (interference between tasks) between than across modalities; however, this effect was only observed when auditory tracking was employed. The results also provided evidence for spatial specific resources, that were independent of input modality.

Isreal's experiment 2 was directly analogous to experiment 1, except that the discrete stimuli were to be counted and ERPs recorded, rather than requiring an RT response. The following main conclusions were drawn from this experiment: (1) Replicating previous results, P300 amplitude declined when the tracking task was performed. (2) Unlike reaction time, there was no evidence for greater interference (reduction in P300 due to tracking) within as opposed to between modalities. More specifically, when the discrete stimuli required an intensity discrimination, P300 amplitude showed the same attenuation across all combinations of tracking and discrete stimuli modalities. (3) When a spatial discrimination was required for the discrete stimuli, a greater attenuation in P300 was observed with the auditory than visual probes, but

this effect was observed with both auditory and visual tracking.

Collectively, these results, (1) converge with data from the previous experiment in suggesting that the auditory ERP may be more sensitive to workload-related effects than the visual, (2) support the conclusion that the P300 is transparent to modality specific interference effects, thereby further emphasizing the endogenous properties of that component, (3) demonstrate the feasibility of an auditory tracking display. While this demonstration does not directly pertain to the ERP, we are pursuing the development and optimization of the auditory display, in an effort to provide technology for reallocating the pilot's processirg demands away from the heavily overloaded visual channel.

2.2. Expectancy and Subjective Probability.

A considerable volume of research conducted in our own laboratory and elsewhere has demonstrated that the amplitude of P300 is sensitive to the "expectancy" or surprise value of stimulus. Its amplitude is increased to the extent that a stimulus provides information that contradicts the subjects "internal model" of the environment. In two experiments described below we have demonstrated that variations in P300 amplitude attibutable to expectancy, can provide information concerning an operator's cognitive model of the environment: information, that is not revealed by overt behavioral responses. In applied contexts, this information could be employed by a sophisticated computer to maintain a model of the human operator's understanding of the environment. Equipped with such information, the intelligent, adaptive system could improve the overall level of system performance. The first of these investigations examines the independence of P300 related indeces of subjective probability and overt probability

decisions; and the second concerns applications of expectancy-related information to programmed instructions. A third series of experiments reported under this heading concerns the influences of the violation of semantic expectancies on the amplitude of a different component of the ERP, the N-200. The latter investigation therefore, extends our basic research into the vocabulary of the ERP.

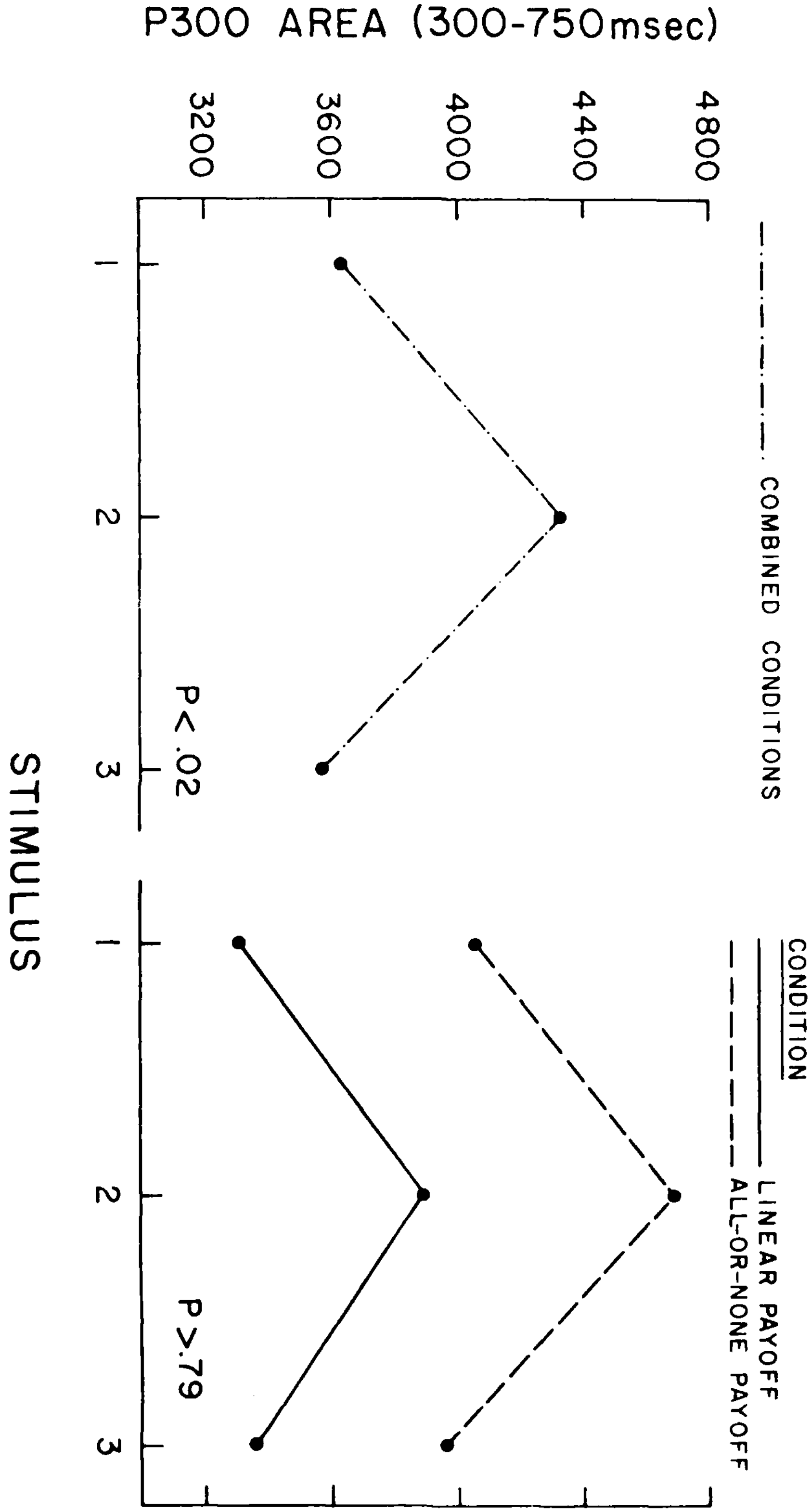
2.2.1. P300 and Decision Making. It is commonly assumed, in the study of subjective probability (SP), that subjects' predictions of future events accurately reflect the SP associated with these events. Yet, evidence suggests that overt predictions are determined by the operation of two independent processes: the perception of probability and the complex motivation and strategies that determine subjective utilities. Overt predictions and SP may, therefore, be discrepant. It would be of value, therefore, to have a direct index of SP. It has been shown that P300 varies inversely with the SP associated with events. In this study we demonstrate that P300 amplitude is not affected by a motivational variable that does affect overt predictions.

Sixteen subjects were required to predict, on each trial, whether a 1, 2, or 3 would appear on a display. The numbers appeared randomly with probabilities .45, .10, and .45 respectively. In one condition, subjects were given bonuses according to an all-or-none (AON) payoff function in which they received one cent if they predicted correctly, or nothing if they were incorrect. In a second condition, bonuses were determined by a linear (LIN) payoff function in which subjects were paid in proportion to the arithmetic difference between their prediction and the number that appeared. The optimal strategy for maximizing payoffs was to

predict 1's and 3's in the AON condition and to predict 2's in the LIN condition. Subjects were not informed of the optimal strategies, but were left to adopt whatever strategy they liked.

EEG was recorded from Fz, CZ, Pz, and Oz (referred to linked mastoids) as well as EOG using a 2.5 second time constant and upper half-amplitude cutoff of 35 Hz. EEG and EOG were digitized at 100 samples/sec for 128 points beginning 100 msec prior to the presentation of a number. Single trials containing excessive EOG artifact were removed off-line prior to averaging.

ERPs were sorted for averaging on the basis of subject, stimulus, electrode, and payoff condition. P300 amplitude was quantified by removing the 100 msec pre-stimulus baseline from each average and then calculating the area under the curve between 300 and 750 msec after stimulus onset. These area measures were then subjected to a repeated-measures analysis of variance (ANOVA). P300 amplitude was significantly larger when elicited by the rare stimulus than by the frequent stimuli for both payoff conditions ($F(2,30) = 5.177$; $p < .02$). This is shown on the left in figure 7. According to our prediction, however, this effect of stimulus probability on P300 amplitude did not significantly interact with the payoff manipulation ($F(2,30) = .237$; $p > .79$). This is shown in the right side of figure 7. It is also interesting to note that presentation of the rare stimulus elicited a longer latency P300 that the frequent stimuli for both payoff conditions. Latencies of P300 recorded at Pz were calculated for each subject, stimulus, and payoff condition and subjected to an ANOVA. Although we made no predictions regarding P300 latency, the results of this analysis were identical with the P300 amplitude analysis, i.e., P300 latency



P300 AREA (300-750msec)
4800
4400
4000
3600
3200
COMBINED CONDITIONS
CONDITION
LINEAR PAYOFF
ALL-OR-NONE PAYOFF
P<.02
P>.79
1
2
3
1
2
3
STIMULUS

FIGURE 7

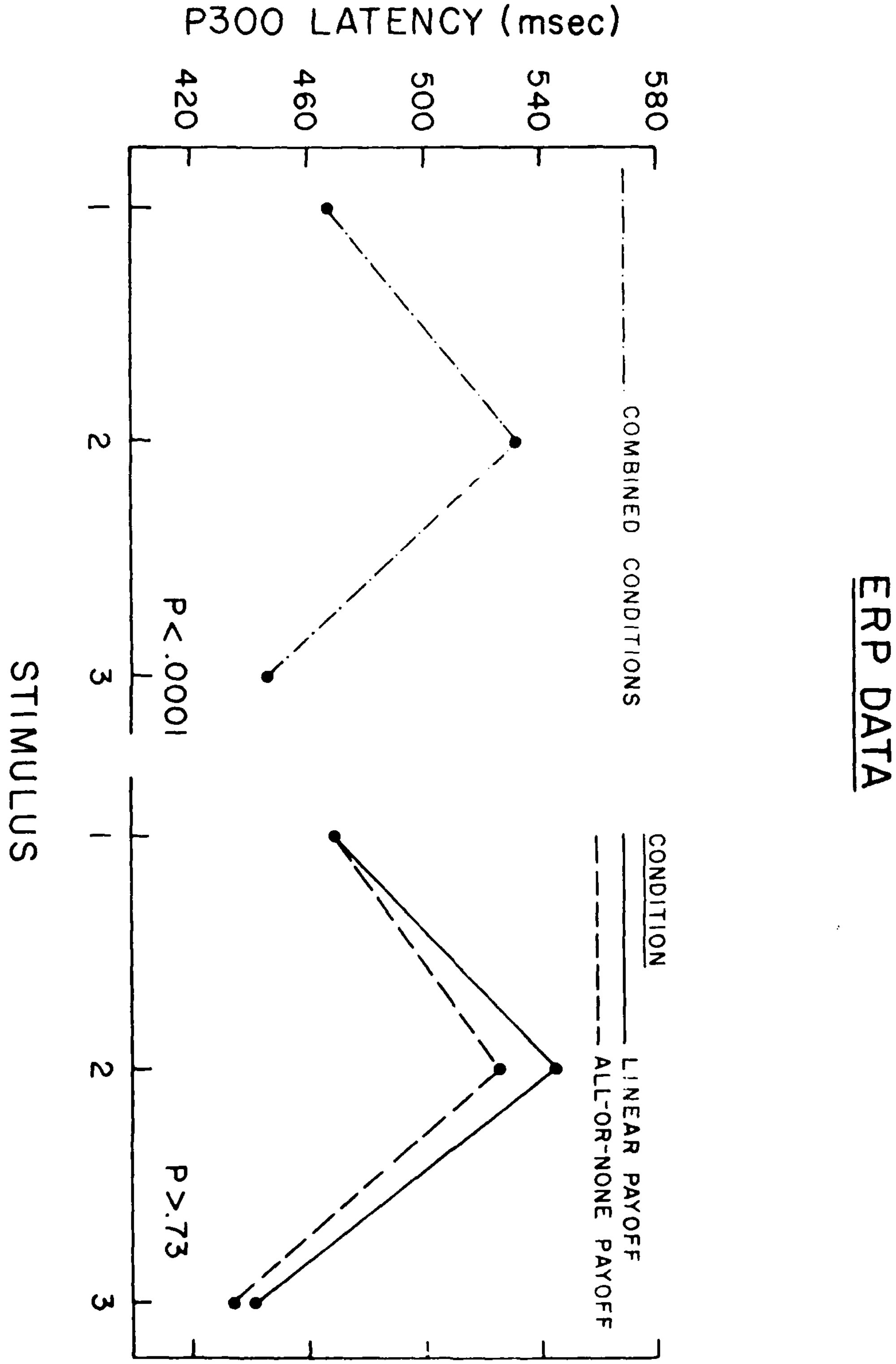

ERP DATA
P300 LATENCY (msec)
580
540
500
460
420
COMBINED CONDITIONS
CONDITION
LINEAR PAYOFF
ALL-OR-NONE PAYOFF
P<.0001
P>.73
1
2
3
1
2
3
STIMULUS

FIGURE 8

BEHAVIORAL DATA

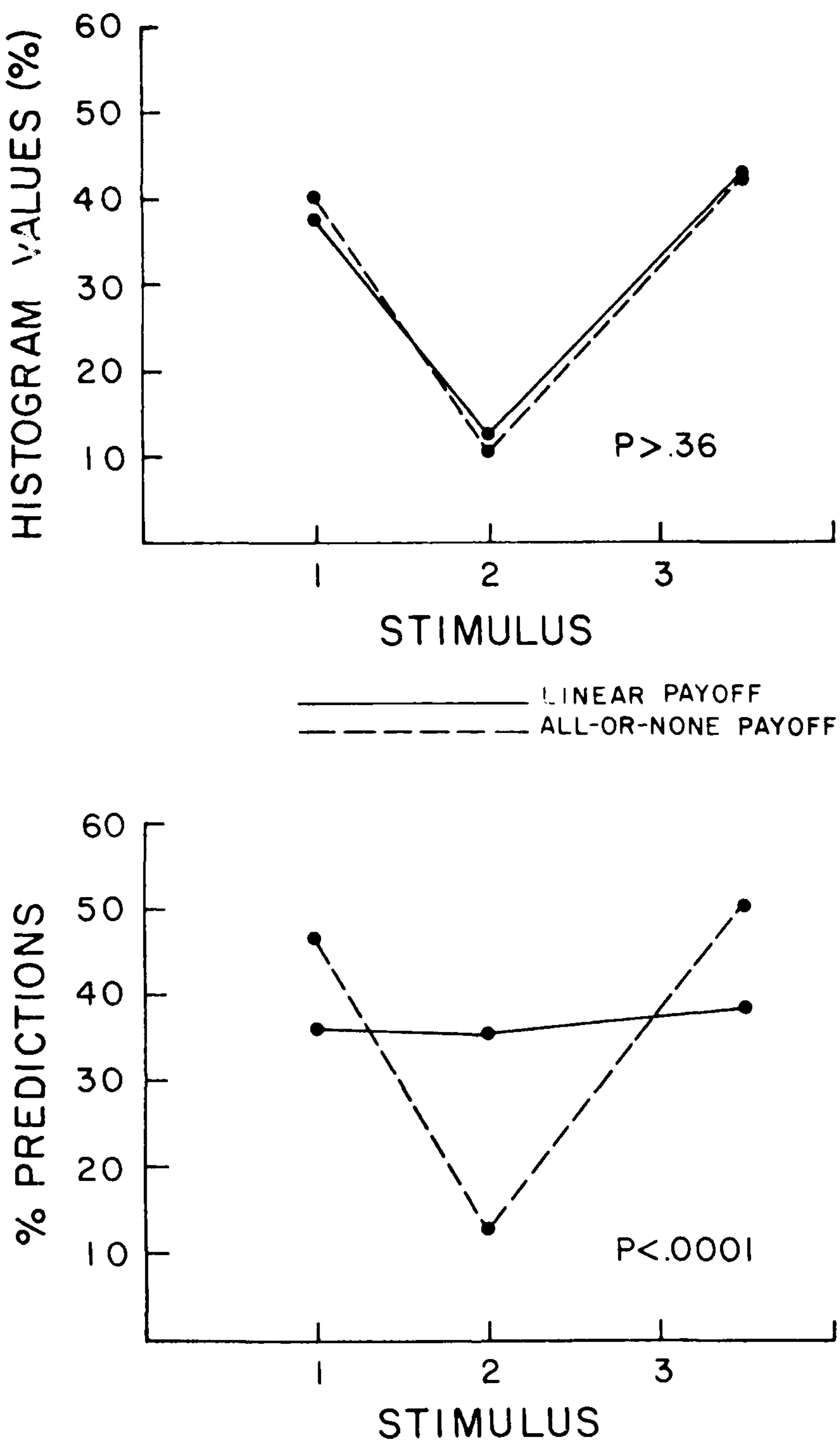


FIGURE 9

was significantly affected by stimulus probablility ($F(2,30) = 19.155$; $p <$ .0001) but this effect did not interact with payoffs ($F(2,30) = .318$; $p >$ .73). (Figure 8). Although in both conditions P300 reflected stimulus probability, subjects' predictions were strongly influenced by payoffs and differed dramatically in the two conditions. The average percentages for predicting a 1, 2 or 3 are shown at the bottom of figure 9. Although predictions varied, subjects were aware of the actual probabilities, and their estimates, given at the end of a block of 100 trials, are shown at the top of figure 9. It is clear from this figure that subjects were aware that the probabilities were actually the same in both conditions.

These results show that, under certain conditions, overt predictions and SP can be dissociated. P300, unlike predictions, reflects stimulus probability consistently regardless of the payoff structure. We conclude then that P300 provides a reliable measure of SP when overt predictions fluctuate.

2.2.2. P300 and Subjective Probability in a Learning Task. The details of this investigation are provided in Appendix D (Horst, Johnson & Donchin). In a paired-associate learning task, subjects responded to each presentation of a nonsense syllable by typing both a three-letter associate and a rating of their confidence that this response was correct or incorrect. Average event-related potentials (ERPs) elicited by the subsequent presentation of the actual paired syllable varied with the interaction of confidence and trial outcome. A larger amplitude P300 was elicited by syllables which informed subjects that they were correct when they thought they were incorrect, than by syllables which confirmed subjects' expectations. That this average ERP result was indeed an effect

on P300 amplitude, and not an artifact of single-trial variability in P300 latency, was confirmed with a trial-by-trial latency adjustment procedure. Consistent with findings from other tasks, P300 amplitude varied inversely with the subjective probability of the ERP-eliciting events.

From these results, it is plausible to envision an adaptive programmed instruction course, in which different "branches" of a branching program are taken given the computer's inference of the subject's state of knowledge of the material. Based on the assumption that a correct answer does not necessarily imply knowledge of the material, if the subject is surprised to know that he was correct, the accuracy of this inference would be improved by utilizing, not only the correctness of subject's answers, but also the ERPs elicited by feedback to correct and incorrect answers.

2.2.3. Category Expectancy and the N200. The P300 component of the ERP elicited by unexpected task relevant events, is commonly preceded by a negative component--the N200. Several investigators reported that the N200 can be elicited by rare events even when they occur beyond the subject's focus of attention. The N200 is often rendered invisible by the overlapping P200. However, it is possible to observe the N200 by forcing an increase in its latency, thus avoiding the overlap with other components. We report a series of studies using this approach. We conclude that N200 is elicited whenever the eliciting stimulus is not a member of a category expected by the subject. The data indicate that the category violations elicit an N200 even when judgments about category membership are not explicitly relevant to the subject's task. We also show that the detection of category violations may underlie the negative component elicited by incongruous terminations of sentences (Kutas & Hillyard, 1980).

In Experiment 1 subjects were asked to identify words that were members of a pre-specified category. The probability that a word will belong to the category was either .75, .50, or .25. In a control series an alphabetic character was presented and the subjects were to indicate whether it was a prespecified letter. The EEG was recorded from Fz, Cz and Pz (referred to linked mastoids), and digitized at a rate of 128 points/second. Recording bandwidth was 0 to 35 Hz, with a 10 sec time constant. In all experiments subjects responded by pressing one of two buttons and reaction time was recorded. Rare events elicited a P300 component which was most prominent at Pz. In addition, a negative component with a latency of 300 msec was elicited by all words that were not members of the expected category of events for which the subject was tuned. The amplitude of this component was greatest at the frontal electrode. We tentatively label this component "N200", and note that its amplitude was independent of the probability of the category violation.

In Experiment 2, subjects were required to indicate whether a stimulus item was a word or a non-word (a pronounceable but meaningless string of letters). In this experiment, 60% of the stimuli belonged to the same category of items, 20% were non-category words, and 20% were non-words. The instructions to the subjects did not refer to the category/non-category distinction; subjects were asked to indicate whether a word or a non-word had been presented. Thus, the task required a lexical decision where both category and non-category words called for the same overt response. The EEG and the overt responses were recorded in the same manner as in Experiment 1. The subjects responded with equal speed to the category and the non-category words. The ERP data, on the other hand, revealed a difference between the

subjects' responses to category and to non-category words. The non-category words elicited a prominent N200 at the frontal and central electrodes which was quite similar to the N200 elicitied by the non-words. The latter also elicited a P300 at the parietal site. The data are consistent with the view that the N200 is sensitive to deviations from the model of the environment, but that only those deviations that are 'task-relevant' elicit a P300 as well.

Kutas and Hillyard (1980) reported that a negative wave is elicited by the incongruous termination of a sentence. It is possible to consider these incongruities an instance of category violations. According to this view, the first six words of the sentences used by Kutas and Hillyard established an expectation that the seventh word would come from a category of "fitting" words. Expectation for a category is violated and a negative wave similar to the N200 observed in Experiments 1 and 2 would be elicited. This hypothesis was evaluated in Experiment 1. In one condition subjects decided whether each of a series of seven word sentences terminated "appropriately" or not. In a second condition, subjects were presented on each trial with a sequence of seven words; the first six were always selected from a single category. The seventh word did, or did not, belong in that category. The subjects indicated whether or not the seventh word came from the category established by the first six words. The probability that a category violation would occur in either condition was .50. The ERPs elicited at the frontal and central electrodes by the seventh word in the two conditions were remarkably similar. A negative wave, very much like that elicited in the previous two experiments, was elicited by the "incongruous" termination of sentences and by a word that violates the

expectation established by the first six words. These three experiments thus extend our basic understanding of the vocabulary of the ERP. They suggest applications to areas in learning where the subjects' knowledge of category membership can be inferred without the explicit requirement of task-related responses.

2.3. P300 Latency.

An important source of information in human engineering is the latency or speed with which perceptual categorizations are made. Slower perception, in a sense represents less efficient performance, and system or task characteristics that prolong latency should be avoided. Previous studies in our laboratory have indicated that the latency of P300 is indeed sensitive to experimental variations in task difficulty, (Heffley, Wickens & Donchin, 1978), or processing complexity (Kutas, McCarthy & Donchin, 1977). These investigations furthermore suggest differences in processing latency in P300 may reveal efficiency or processing changes that are opaque to reaction time measures. The mental chronometry of P300 and reaction time is explored in the following experiment.

2.3.1. P300 and RT Latency. (Details are provided in Appendix E, McCarthy & Donchin, in press). In this experiment, subjects performed a choice reaction time task, to the stimulus words "right" or "left". The stimulus words were assigned to responses in either a compatible (respond with right hand to "right" and left to "left") or incompatible regime (respond with the right hand to "left" and left to "right" respectively). In addition, stimulus words were presented in either a clear or a masked format. Reaction time was prolonged by both the

incompatibility and the masking variable. P300 latency was prolonged only by the former variable. The results then establish the basic independence of P300 latency from response processes.

The utility of P300 latency information in an applied setting is suggested by an experiment of McCarthy and Donchin (1979). Subjects performing a speeded classification task (discriminating frequent male names from infrequent female names) were placed under speed stress. Under these conditions, subjects make more errors but the errors are almost exclusively rare stimuli categorized as frequent. In addition these error trials (rares called frequent), show three other characteristics that discriminate them from the other "frequent" responses (frequents called frequent). (1) They show large P300s. (2) The reaction times are particularly fast. (3) The P300 is of relatively longer latency. A decision logic is demonstrated whereby all frequent responses (both correct and errors) are examined without knowledge of their correctness. Those trials showing this particular configurations of features are then identified by the algorithum as errors. This identification is performed with a high degree of accuracy. Out of 367 error trials, 343 are correctly identified as errors on the basis of the feature analysis.

The paradigm provides demonstration of how information provided by P300 can be used <u>in conjunction with</u> information provided by the overt manual responses, to facilitate system performance. In this instance the facilitation is achieved by the monitoring and correction of classification errors made by an operator under speed stress.

2.4. Movement Related Potentials.

The ultimate goal of this research area is to determine the relationship between movement-related brain potentials and voluntary movements. Equipped with such information, an intelligent on-line computer might, for example be able to discriminate voluntary intentional deflections of a joy stick control, from involuntary accidental movements, and in this way be able to filter out the latter from exerting control over the system. Our initial objective was to establish some basic relations between hand of control, movement-related potentials recorded from lateral electrodes, and handedness.

Levy and Reid (1976) postulate that the organization of motor pathways and the control of movement varies in those persons who write using the inverted handwriting posture (hand above the line and pencil tip pointed toward the bottom of the page). Unlike noninverted-writing (hand below the line and pencil tip pointed toward the top of the page) persons who are considered to have predominately crossed pyramidal motor pathways and contralateral control of movement, those persons who are inverted-writing are hypothesized to have largely uncrossed pyramidal tracts and ipsilateral control of movement. Although the model has been interpreted broadly to include all distal limb movements, Levy and Reid focus attention on the control of handwriting.

We tested this model by analyzing the readiness potential in subjects identified on the basis of handedness and handwriting posture. The RP is a slow negative change in activity measured at the scalp prior to the initiation of a self-paced, voluntary movement. It is largest at scalp sites over the motor cortex contralateral to the moving limb and is

considered to reflect the direction of control in the motor system. In our first experiment, three groups of eight males were used: one group of noninverted-writing right-handers (RN), one of noninverted-writing left-handers (LN), and one of inverted-writing left-handers (LI). Each subject was required to perform a self-paced unimanual squeeze, the subject squeezed a dynamometer 96 times with the left and right hand in separate blocks of trials. Levy and Reid's model predicts that noninverted- writing subjects will have contralaterally dominant RPs, whereas inverted-writing subjects will have ipsilaterally dominant RPs. Our results revealed, however, that in all subjects, without exception, the RP associated with the self-paced squeeze was contralaterally larger. The inference drawn from this finding is that control of this movement originates from the motor cortex opposite the moving limb in both noninverted- and inverted-writing persons. Thus, our data fail to support Levy and Reid's model.

However, since Levy and Reid can be interpreted as hypothesizing ipsilateral control of handwriting movements only, the failure to find ipsilaterally dominant RPs in inverted-writing subjects producing a squeeze is not refutation of their model. Consequently, we conducted a second experiment in which male subjects (4 RN, 6 LN, 7 LI), identified on the basis of handedness and handwriting posture were required to perform a number of unimanual self-paced movements. Each subject wrote two words, "he" and "hand", connected dots either 1 or 2 inches apart, flexed his wrist, and squeezed a dynamometer. In all conditions but handwriting each subject was tested with the dominant and nondominant hand. 56 trials were performed in each condition.

Again, as in Experiment 1, we found no support for Levy and Reid's model. With the exception of one subject, the RP associated with each movement was contralaterally dominant. One subject, a noninverted-writing left-hander, produced ipsilaterally larger RPs in the handwriting and dot connection tasks. Interestingly, the RP was contralaterally larger in this subject for all other movements. Thus, although we did not find support for the relationship between handwriting posture and ipsilateral control of movement, including handwriting, we did identify one subject who apparently does have ipsilatlateral control of certain distal limb movements. We have no ready explanation for this difference. All subjects were chosen on the basis of strict criteria: male, strongly dominant, use dominant hand for writing and throwing, and no family history of left-handedness.

Since the number of trials used in Experiment 2 was relatively small, we conducted a third experiment in which subjects wrote "he" and "hand", and performed self-paced squeezes with the left and right hands. Our data again fail to support the Levy and Reid model. In this study, we identified an inverted-writing right-hander (they are rare, approximately one percent of the right-handed population) and recorded the RP from this subject. He, too, produced contralaterally dominant RPs in each movement condition.

In addition to testing the hypothesis suggested by the Levy and Reid model, we are characterizing the activity measured at the scalp during the execution of each of these various movements. Previous research has focused on the premovement activity, however, recent work suggests that positive going potentials characterize the movement period. One laboratory, however, reports a sustained negativity in association with movement

(Grunewald, et al.). This negativity, called the goal-directed movement potential (GDMP), was reported in a movement toward the body's midline. The positivivity reported by other investigators is seen during discrete movements, such as finger flexions. Thus, we required that our subjects perform both discrete and sustained movments (e.g., squeeze versus handwriting). Further, since there is evidence to suggest that limb movements toward the body's midline are controlled by different cerebral mechanisms than are those away from the body's midline, we required that our subjects connect dots by moving either from the outside dot to the inside dot (toward the midline) or from the inside dot to the outside dot (away from the midline). The movement-related activity in all conditions except that requiring movement toward the midline was positive going. During movement toward the midline, however, the activity was negative going, like that reported by Grunewald, et al. Since our analyses of these data are not complete, any conclusions are premature. Subsequent tests of these various movements are being conducted to see if the differences can be replicated.

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4. List of Appendices

Appendix A: Wickens, C. D., Heffley, E., Kramer, A. & Donchin, E. The event-related brain potential as an index of attention allocation in complex displays. Proceedings, 24th Annual Meeting of the Human Factors Society. Santa Monica, Calif., 1980.

Appendix B: Horst, R. & Donchin, E. Beyond Averaging II: Single-trial classification of exogenous event-related potentials using stepwise discriminant analysis. Electroencephalography and Clinical Neurophysiology, December, 1979.

Appendix C: Isreal, J. B. Structural interference in dual task peformance: Event-related potentials, behavioral and subjective effects. Unpublished Ph.D. Dissertation. Univeristy of Illinois, 1980.

Appendix D: Horst, R., Johnson, R. & Donchin, E. Event-related brain potentials and subjective probability in a learning task. Memory and Cognition, in press.

Appendix E: McCarthy, G. & Donchin, E. A metric for thought: A comparison of P300 latency and reaction time. Science, in press.

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